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Development of Computer Codes to Model Dynamics of the Earth's Magnetosphere

April 1989

by

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ABSTRACT

The objective of the research has been to develop models of plasma processes in the earth's magnetosphere and ionosphere to enable us to understand processes responsible for auroral and magnetic substorm phenomena. One major accomplishment has been the tentative identification of the process for generation of the electric potentials that accelerate auroral electrons. Numerical simulations suggest that the accelerating potentials are generated by the differential east-west displacement of magnetic field lines caused by currents in the sunward/anti sunward direction in the plasma sheet. This displacement gives auroral field lines a component parallel to the convection electric field, so that auroral electrons are, in effect, directly accelerated by the convection electric field. Another major accomplishment is a numerical model of auroral precipitation. The model suggests that the field-aligned accelerating potentials are maintained primarily by electron inertia and secondarily by the magnetic mirror force. Electron acceleration is through a laminar DC potential drop. Electrostatic beam-plasma interactions occur when the electrons encounter the upper ionosphere where the flux-tube plasma density begins to increase with decreasing altitude. Auroral beam electrons thermalize in this region, but there is little time-averaged potential change in this region. The simulations indicate that "anomalous resistivity" plays little role in electron acceleration processes. The auroral simulation model indicates that the auroral beam may excite upper hybrid electrostatic waves, which may stochastically accelerate a portion of the electron beam to many tens of keV. Other spinoffs of this research and new research initiatives are described in this report.

1. Project Objectives

The objective of this project is to develop particle codes to model kinetic processes in the earth's magnetosphere relating to the aurcra, geomagnetic storm phenomena and energy transfer processes from the solar wind to the magnetosphere. This work can be used in concert with the results of global scale MHD modeling to understand the dynamical processes associated with geomagnetic storm phenomena. The ultimate objective is to develop an ability to predict "weather" in the magnetosphere just as we are now able to predict the weather in the lower atmosphere.

Before one can contemplate the development of a predictive model of the magnetosphere, it is first necessary to identify and understand the important physical processes in the magnetosphere. The approach used in this project is to develop an understanding of a variety of heretofore poorly understood processes in the magnetosphere by isolating individual problems and developing numerical models which elucidate the important phyisical processes. In effect we are constructing pieces of a mosaic, which when fitted together will reveal a coherent picture from which a substantive global model of the magnetosphere can be developed.

The effort reported here has focused on the identification of processes responsible for the acceleration and precipitation of auroral electrons. A major question under investigation is the mechanism that establishes and maintains the field-aligned potential differences that accelerate the electrons responsible for the discrete aurora. This question can be subdivided into two parts: One is what is responsible for creating potentials across field lines? The other is given the existence of potential differences across magnetic field lines, what maintains field-aligned potential differences? Since magnetic field

lines terminate in a conducting ionosphere, any process that creates potential differences across field lines will cause field-aligned currents to flow. Field-aligned potential differences will then result from any process that impedes the flow of field-aligned current. An understanding of the electron acceleration mechanism implies an understanding of what impedes field-aligned electron current flow.

The research findings to be reported in the next section have shown two necessary conditions for the production of aurora. One is a convection electric field. The presence of a convection electric field is known to depend on the linkage between the interplanetary magnetic field and the Earth's magnetic field. A related investigation has therefore been to use one of the codes developed for use in one of the above projects to model tearing mode instabilities on the dayside magnetopause. The other necessary condition is the presence of a population of particles in the lobe regions of the magnetosphere to replenish the plasma sheet. The presence of O^+ in the plasma sheet provides strong evidence that a major portion of the plasma, particularly on closed field lines, originates from the ionosphere. A new project objective has been to model the transport of plasma from the polar ionosphere to the magnetotail.

2. Research Accomplishments

This section presents summaries of research work completed with AFOSR support. The details are reported more fully in the emanating from this project listed in Section 4 of this report. The publication reference numbers corresponding to each subsection are indicated in the headings. All work reported in this section has been published or is in press. In addition, I discuss the implications and insights gained from this work subsequent to its

submission for publication. Work that is still in progress at the close of this grant is described in Section 3.

2.1 Generation of Auroral Accelerating Potentials (Publications 1 and 2)

A two-dimensional electromagnetic particle code has been used to model processes in the earth's magnetotail. The code is in the Darwin Approximation, which means that the transverse part of the displacement current is neglected in the field equations. This makes the code suitable to modeling electromagnetic processes in which radiation is unimportant. The code includes three components of the electromagnetic field, as well as the electrostatic field. The Hamiltonian formulation is used, in which particle phase space positions are described by two position coordinates and three components of the conjugate momentum.

The code was modified from that used by Swift [1986] to model tearing mode instabilities. The major modifications were the inclusion of a background magnetic field component normal to the current sheet. A normal field is necessary in order that there be a magnetic field connection linking the plasma sheet to the ionosphere. The other major modification was a provision for flow-through particle boundary conditions in order to provide charge carriers on the field lines linking the plasma sheet with the conducting boundaries representing the ionosphere. The code was used to model a portion of the earth's magnetotail between 10 and 20 earth radii.

Simulations using this code exhibited a new and potentially important mechanism for the generation of potential differences across the magnetic field lines in the magnetotail. Currents flowing parallel to the plasma sheet and in the plane of the simulations are generated by the influx of particles from the

magnetotail lobes. Due to their smaller mass, electrons pick up the enhanced ExB drift in the sunward direction in the plasma sheet more readily than ions. This gives rise to an x-directed current. The current generates a magnetic field in the magnetospheric y-direction (dawn to dusk), which results in the looping of the magnetic field lines out of the plane of the simulation. Electrons tend to cluster in these field line excursions because of the presence of the convection electric field. Because electrons gain kinetic energy in the convection field, their streaming velocity increases, which in turn increases the current. We thus have a positive feedback effect. Because electrons tend to collect in the field excursions, electrostatic fields also develop. As the amplitude of the disturbance grows, structure develops in the x-direction, so that potential differences develop across field lines.

The potential field generated is shown in the contour plot of Figure 1. The potentials are considerably larger than characteristic plasma sheet ion energies. Unfortunately, it was not possible to show that these potential structures would propagate to ionospheric altitudes because of the boundary conditions used in the simulation. However, these simulations did link the generation of potential fields to the displacement of magnetic field lines in the east-west direction. A possibly important clue as to the origin of auroral accelerating potentials may also be the results of conjugate flight experiments reported on by Stenbaek-Neilsen et al. [1972] in which they report the apparent east-west displacement of auroral forms up to 300 km. This displacement appears to depend on time and substorm conditions thus indicating a longitudinal motion of field lines. The simulations described in this section show the development of an asymmetric displacement and shearing of field lines. The auroral electrons may simply be directly accelerated by the component of the convection

electric field parallel to the magnetic field, resulting from the shearing of the magnetic field. The continuation of this work is described in Section 3.1.

2.2 Tearing Mode Instabilities on the Dayside Magnetopause (Publication 3)

The electromagnetic code used to conduct the investigation described in the previous subsection has been used to investigate tearing mode instabilities in asymmetric tangential discontinuities of the type observed on the dayside magnetopause. On the upstream side a plasma $\beta = 3$ is assumed, while the magnetosphere side is assumed to be a vacuum, with $\beta = 0$. The sum of the magnetic field and plasma pressure is assumed to be the same on both sides, as required for equilibrium. The plane of the simulation was perpendicular to the current sheet supporting the field rotation. We then systematically studied the effect of varying the strength of the guide field, perpendicular to the plane of the simulation. This allowed us to investigate the effect of differing interplanetary B_y on the rate of magnetic reconnection. The results, as expected showed that the tearing mode growth rate depended strongly on the angle of field rotation across the tangential discontinuity, with the largest growth rate for a 180° rotation. Another important finding was that the number of field lines connected also depended strongly on the magnitude of the field rotation, with the greatest connection favoring the 180° rotation. This indicates that the greatest flux linkages will occur not only most readily, but most strongly, on portions of the magnetopause with opposite field polarity.

2.3 Auroral Acceleration Model (Publication 4)

A significant accomplishment has been the development of a numerical model for auroral precipitation. This is a two-dimensional electrostatic code which traces the motion of particles in a converging magnetic field and self-consistent electrostatic field. A unique feature of this model is that it uses a curvilinear coordinate system with one set of coordinate lines everywhere parallel to the magnetic field and the other coordinate direction everywhere perpendicular. The ions are assumed to be infinitely massive and immobile.

The modei showed that the electrons, which are believed responsible for the discrete aurora, are modified by two processes: In the region above the ionosphere, where the number of electrons per flux tube length increases with altitude due to the expansion of the area of a flux tube cross section, the electrons are accelerated through a laminar, field-aligned potential difference, extending over a distance of several thousands of kilometers. When the accelerated electrons encounter a region of increased plasma density, representing the upper ionosphere, a variety of electrostatic instabilities are excited by beam-plasma interaction. If the plasma is assumed uniform in directions transverse to the magnetic field, large amplitude Langmuir plasma oscillations are seen. This is a feature which is observed in most particle code simulations conducted by other investigators. These waves are effective in thermalizing the particles in directions parallel to the magnetic field. However, when a variation in the background ion density perpendicular to the magnetic field is introduced, the Langmuir waves largely disappear, and waves along the upper and lower hybrid resonance curves are seen. Lower hybrid waves are preferentially excited and produce some heating of the electron beam perpendicular to the magnetic field. The upper hybrid waves are also excited when the electron plasma frequency approaches the gyrofrequency. These waves

result in very rapid heating of the electron beam perpendicular, as well as parallel, to the magnetic field. Another outcome of the ion density variation perpendicular to the magnetic field is that the largest field-aligned potential differences, and hence the largest electron acceleration, occurs on field lines where the ion density is a minimum.

This model has been successful in tying together a number of seemingly unrelated observations concerning auroral precipitation. First, it has reproduced the coordinated observations of the DE-1 and -2 Satellites which showed that parallel electron acceleration occurs over very extended field-aligned paths with little heating of the beam. The model shows this to be a simple consequence of increasing flux-tube electron content with altitude in the region above the ionosphere. The model also shows that the reason Langmuir waves are not seen in the auroral ionosphere is because in the auroral ionosphere, the ionization density shows large variations perpendicular to the magnetic field. Instead, waves on the lower hybrid resonance curve are excited, which are observed. Some of the wave energy gets refracted away from the resonance cone and can propagate to the ground as electromagnetic waves, which are observed as auroral hiss. Moreover, the model has shown that larger field-aligned potential differences occur on field lines with lower plasma content. This is consistent with observations by the ISIS satellite of plasma density minima in regions of auroral kilometric radiation, which are in turn associated with auroral precipitation.

An interesting result of potential interest to the Air Force is the prediction that the discrete aurora might be a source of intense upward fluxes of energetic electrons. The model indicates that under certain circumstances electrostatic waves on the upper hybrid resonance curve will be excited. These

waves produce a rapid perpendicular heating of the electrons, and the electrons are forced upward by the magnetic mirror force. Upward fluxes of electrons of several tens of keV energy could have an impact on sensors aboard Air Force satellites. Figure 2 shows a contour plot of the two-dimensional velocity distribution function computed in the simulations. A substantial fraction of these electrons have energies considerably in excess of the down-going electrons. Atmospheric scattering, by contrast, would only degrade the electron energy.

2.4 The Production of Very Energetic Electrons in the Aurora (Publication 5)

The simulation results described above indicate that under some circumstances, the discrete aurora should be a source of very energetic electrons. This is a phenomenon, which if it exists, should be very easily observable. I described my simulation results to David Gorney of Aerospace Corporation and indicated what should be observed. As it turned out he had observed instances in the S3-3 Satellite data set in which electron fluxes with energies of many tens to a couple of hundred keV were observed when the satellite was passing through an inverted-V event as shown in the E-t spectrograms of Figure 3. We then conducted a more systematic search through the S3-3 E-t spectrograms for additional events, in which we found instances of such events.

The analysis indicated very energetic electrons were produced at altitudes between 400 and 5000 km. In some of the events electron velocity distribution function data was available, which showed conical distributions with symmetry between up- and down-going populations, as shown in Figure 4. We interpret the

down-going electrons as having mirrored from the conjugate hemisphere. Since the electrons are moving at a substantial fraction of the speed of light they can mirror between conjugate hemispheres in a small fraction of the satellite spin period time that it takes to scan all pitch angles. This provides strong evidence that aurora occurs on closed field lines

3. Work in Progress

During the period of this grant, there were additional projects undertaken for which there was insufficient time to bring to a state of completion by the expiration of the grant. This work is reported here, because it represents a substantial effort; and because it is still being pursued, it will eventually contribute to the overall goals of the project.

3.1 Generation of Auroral Potentials

The major limitation of the simulation described in Section 2.1 was that the magnetic field lines were anchored in the boundary by the boundary conditions on the vector potential. As a result, the code was incapable of showing the propagation of the accelerating potentials to ionospheric altitudes. The new effort is the development of a model which we think will overcome this difficulty. The distinctive feature of the new model will be the introduction of a collision frequency into the particle equations of motion. In the regions representing the plasma sheet and magnetotail lobes, the particles will continue to move in a collisionless environment. However, at distances far enough removed from the plasma sheet, particles will become immobilized due to collisions, to represent the effect of the passage of geomagnetic field lines, first through a conducting ionosphere and then through an insulating

atmosphere. The particle boundary conditions are in effect imposed where the collision frequency becomes larger than the particle gyrofrequencies. The field boundary conditions, where the magnetic field lines are tied, representing the conducting interior of the Earth, are imposed outside the particle boundaries. This will allow displacement of magnetic field lines in the ionosphere and currents to circulate through the ionosphere.

An existing two-dimensional electromagnetic code has been installed at the San Diego Supercomputer Center by a Ph.D. student and run over the NSF net. We are now in the process of modifying to include the effect of a magnetic field normal to the current sheet and particle collisions.

3.2 On the Origin of Multiple Auroral Arcs

The auroral precipitation model described in Section 2.3 and Appendix A4 has been generalized to include the effect of finite mass ions. This is to follow up on the finding that electrons would be accelerated to higher energies on flux tubes of low ion density. Because of the larger potential differences, ions would also be accelerated to higher velocities on these field lines. Flux conservation would require a lower ion density on these field lines. A positive feedback mechanism would occur, because lower ion densities would result in larger potential differences along these field lines. This would provide a mechanism for the spontaneous growth of transverse potential and density variations. This could account for the filamentation of precipitation regions and provide an explanation for the appearance of the fine structure and multiplicity of auroral arcs. The code described above has been extended to include mobile ions and strongly magnetized electrons.

The results of running the code show that potential variations spontaneously develop transverse to the magnetic field on perpendicular size scales large enough to leave the ions strongly magnetized. The results suggest that discrete auroral arcs develop within broader inverted-V electron precipitation regions, with auroral arcs being in regions of more energetic electron precipitation.

3.3 Transport of Polar Cap Ionization

A major new initiative is the modeling the escape of ions from the polar cap ionosphere and injection into the plasma sheet. Recently Cladis [1986] has shown by use of single particle trajectory calculations that the convection electric field will result in the ejection of ions, including O^+, from the polar cap ionosphere. Particles are accelerated parallel to the field lines and convected by the ExB drift onto the near-earth plasma sheet. Simulations described in Section 2.1 indicate that many processes associated with the expansive phase of the auroral substorm require both the presence of a driving convection electric field and injection of plasma from the lobes of the magnetotail. It is my opinion that the expansive phase of the auroral substorm coincides with the arrival of ions recently ejected from the polar cap. The delay time between the southward turning of the IMF and enhanced convection and the expansive phase of the substorm is consistent with the transit time of ions from the polar cap to the near-earth plasma sheet.

I have formulated a two-dimensional, global-scale, fluid model for the plasma escape from the polar cap, which should permit the quantitative evaluation of the fluxes of ions from the polar cap to the plasma sheet. The convection electric field drift introduces a centrifugal force term into the

Navier-Stokes equation. For a 50 mV/m polar cap electric field, the centrifugal and gravitational acceleration terms balance at an altitude of 6000 km. Plasma above this altitude will be accelerated out into the magnetotail lobes. The computational problem has been reduced to the solution of a series of one-dimensional fluid equations for the density and field-aligned flow velocity for each ionic species.

I currently have a version of the code running which transports O^+ and H^+ number density and flux from the ionosphere to the distant magnetosphere. Preliminary results show that the centrifugal force is indeed effective in ejecting H^+ into the magnetosphere. Plasma transport from the topside ionosphere to the plasma sheet takes less than an hour from the time of field line opening in a 50 mV/m electric field. The code does not indicate the ejection and transport of O^+ at normal ionospheric temperatures, which indicates that there must be additional anomalous heating sources in the ionosphere to account for the storm-time presence of O^+ in the plasma sheet.

One very interesting result is that as plasma is transported over the polar cap, it is lifted on the dayside because the ExB drift has an upward component. This reduces the charge-exchange depletion of O^+ because of the reduced atmospheric density. As the plasma passes over the geomagnetic pole, there is a downward component of the ExB drift and a compression of the plasma because the downward motion is inhibited by collisions with the neutral atmosphere. The result is that the F-region density maximum is slightly higher on the nightside of the polar cap than it is on the dayside, even though the plasma comes from the dayside. The upward and downward motion may be a partial explanation of the AFGL observations [Weber et al., 1984] of the anomalously

large polar cap density blobs seen in connection with rapid antisunward plasma convection

4. Publications Supported by AFOSR-86-0037

Swift, D. W. and C. Allen, Interaction of the plasma sheet with the lobes of the earth's magnetotail, J. Geophys. Res., 92, 10,015, 1987. [1]

Swift, D. W., Particle simulation of plasma processes in the earth's magnetotail, Computer Physics Communications, 49, 173, 1988. [2]

Swift, D. W., A numerical model for auroral precipitation, J. Geophys. Res., 93, 9815, 1988. [3]

Allen, C. W. and D. W. Swift, A particle simulation of the tearing mode instability at the dayside magnetopause. To be published J. Geophys. Res., 94, 1989. [4]

Swift, D. W. and D. J. Gorney, The Production of Very Energetic Electrons in the Aurora, J. Geophys. Res., 94, 2696, 1989. [5]

5. Personnel Associated with the Project

The principal investigator has charged approximately one-fifth time. This grant has been the primary support of Clinton Allen, a post doctoral research associate, from December '85 until his departure from the Geophysical Institute in June of 1988. A new Ph.D. candidate graduate student, Dante Garrido, has been supported by the project June 1988 to the end of the Grant in March of 1989. He has has the primary responsibility for carrying out the work described in Section 3.1.

6. Interactions

This project has provided support for the following presentations and collaborative efforts:

Swift, D. W., Interaction of the plasma sheet with the lobes of the earth's magnetotail, Presented at the Fall 1986 Meeting of the American Geophysical Union in San Francisco, CA

I presented seminars on the topic of Appendix Al at UCLA and University of Maryland in July of 1986

Swift, D. W., Particle simulation of plasma processes in the earth's magnetotail, at the Third International School for Space Simulations, Beaulieu, France, June 22 - 27.

Swift, D. W., Acceleration of auroral electrons in DC electric fields, at the Fall 1987 meeting of the American Geophysical Union in San Francisco, CA., December 7 - 11.

Allen, C. W. and D. W. Swift, A particle simulation of the tearing mode instability at the dayside magnetopause, to be presented at the Fifteenth IEEE International Conference on Plasma Science, Seattle, WA, June 6 - 8.

I presented seminars in March of 1988 at Aerospace Corporation and Air Force Geophysics Laboratory entitled "A numerical model for auroral precipitation", the topic of the reprint in Appendix 4

The paper of Appendix 5 was a collaborative effort with David Gorney of Aerospace Corporation

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Cladis, J. B., Parallel acceleration and transport of ions from the polar ionosphere to the plasma sheet, Geophys. Res. Lett., 13, 893, 1986.

Stenbaek-Nielsen, T. N. Davis and N. W. Glass Relative motion of auroral conjugate points during substorms, J. Geophys. Res., 77, 1844, 1972.

Swift, D. W., Numerical simulations of tearing mode instabilities, J. Geophys. Res., 219, 1986.

Weber, E. J., J. Buchau, J. G. Moore, J. R. Sharber, R. C. Livingston, J. D. Winingham and B. W. Reinisch, F-layer ionization patches in the polar cap, J. Geophys. Res., 89, 1683, 1984.

FIGURE CAPTIONS

Figure 1. The end stage of a simulation of the Earth's plasma sheet. All plots are in the noon-midnight plane. (a) Contours of the magnetic vector potential, which show the magnetic field lines. (b) Scatter plot showing he ion positions. (c) Contours of the y-component of the magnetic field, perpendicular to the plane of the simulation. (d) Contours of the electrostatic potential.

Figure 2. (a)A contour plot of the accelerating potential. Electrons are accelerated from right to left. (b) The velocity distribution of electrons that have been accelerated and heated as a result of wave-particle interactions in the ionosphere. (c) The velocity distribution of electrons in the magnetosphere that have been reflected from the ionosphere.

Figure 3. An E-t spectrogram of an energetic electron event imbedded in an inverted-V event, indicated by the arrow. Notice that some coincident electron fluxes also appear in the 235 keV channel.

Figure 4. An electron velocity distribution function taken during the event shown in figure 3. The contour intervals are on a logarithmic scale, 1/3 decade apart. Positive $v_{\parallel}$ is upward.

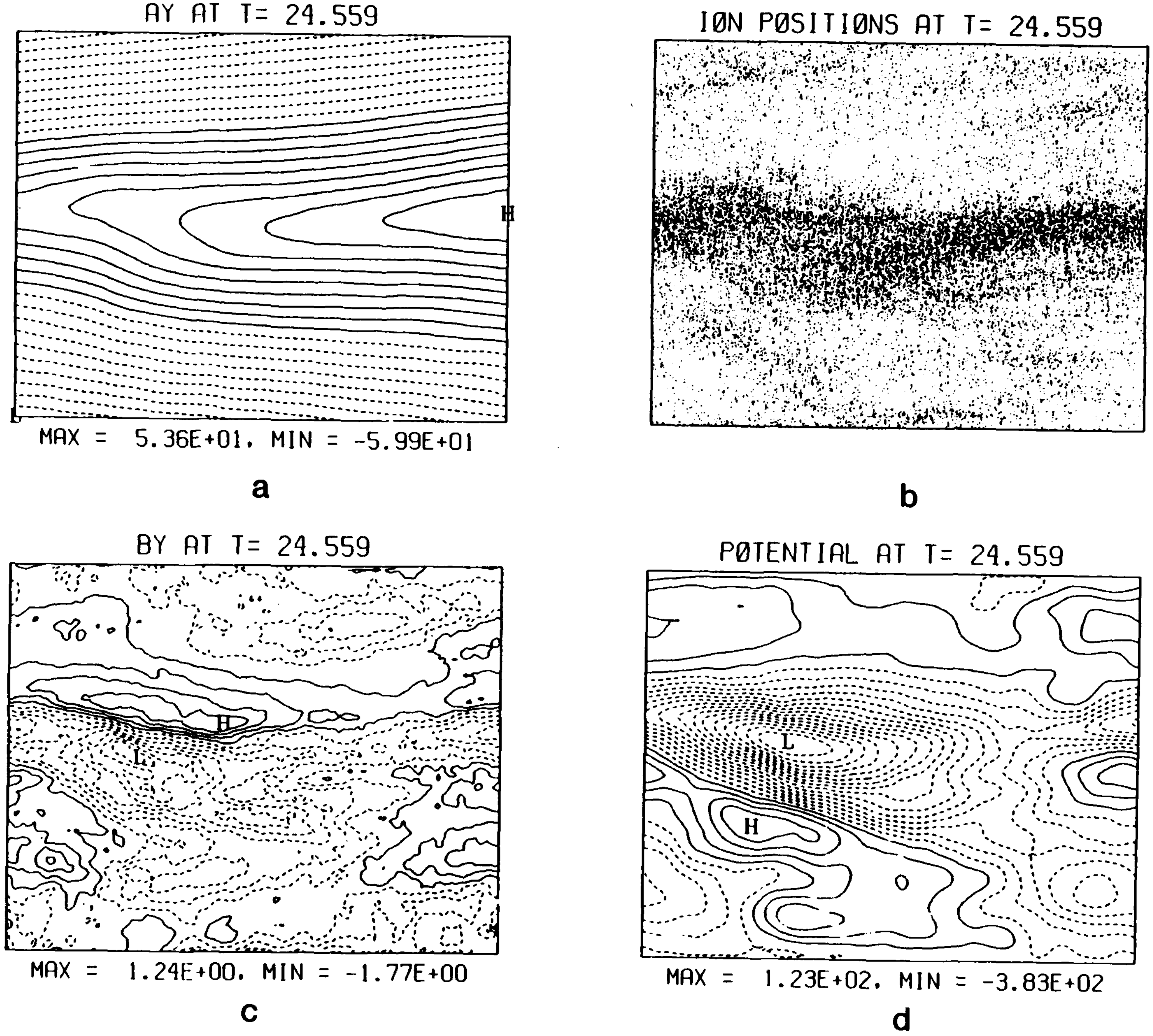
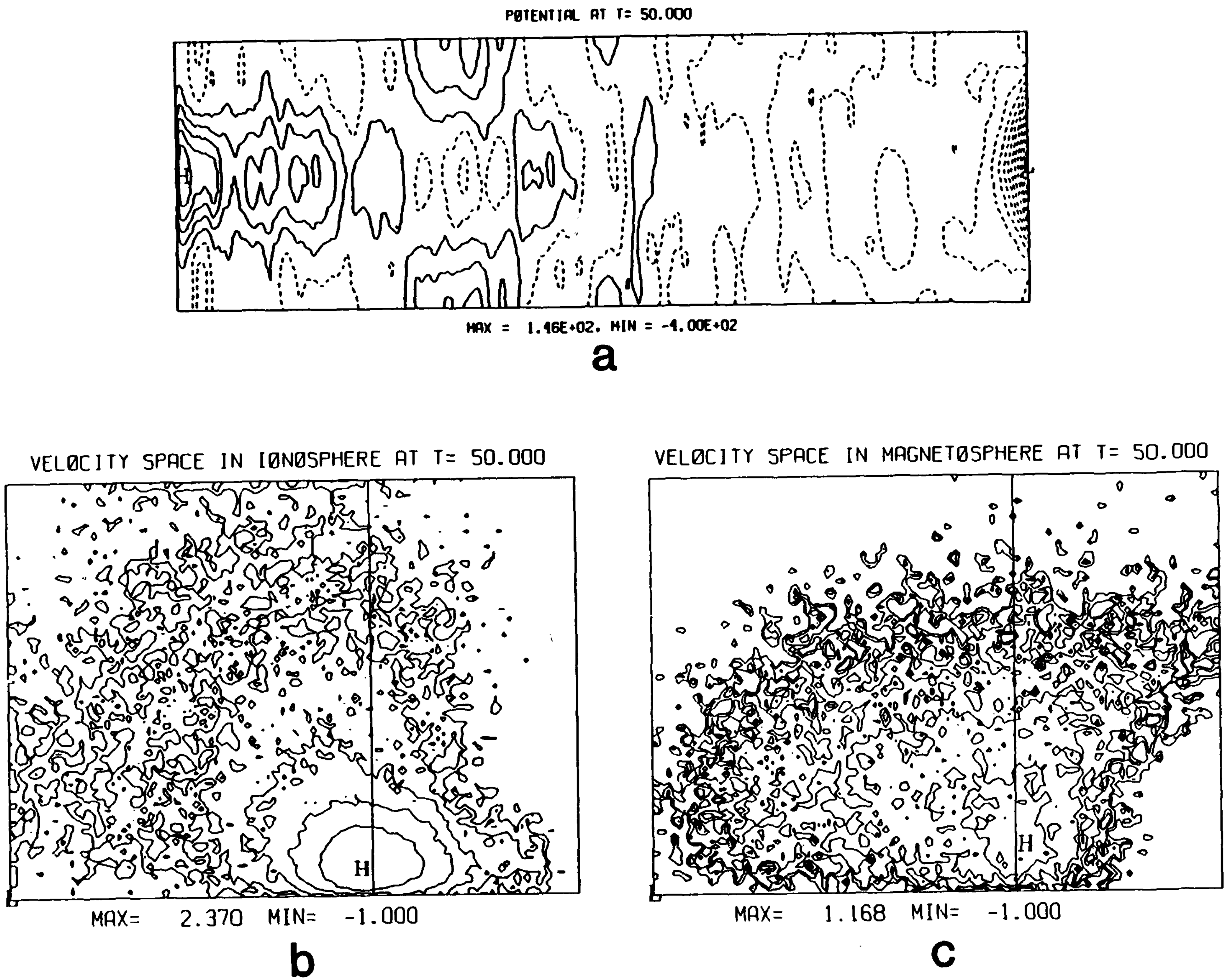
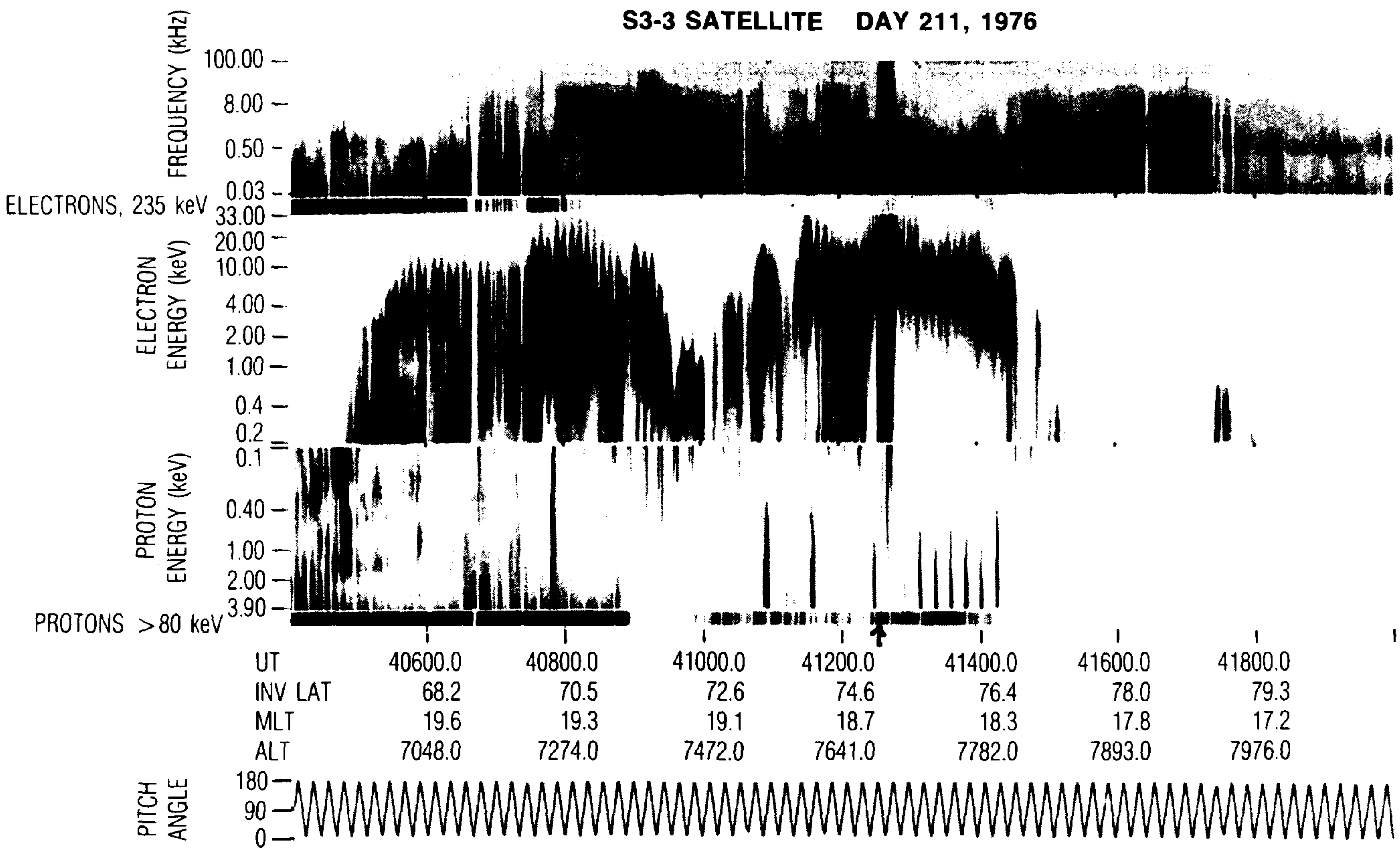

AY AT T= 24.559
H
L
MAX = 5.36E+01, MIN = -5.99E+01
a
IØN PØSITIØNS AT T= 24.559
b
BY AT T= 24.559
H
L
MAX = 1.24E+00, MIN = -1.77E+00
c
PØTENTIAL AT T= 24.559
L
H
MAX = 1.23E+02, MIN = -3.83E+02
d

Figure 1



PØTENTIAL AT T= 50.000
MAX = 1.46E+02, MIN = -4.00E+02
a
VELØCITY SPACE IN IØNØSPHERE AT T= 50.000
H
MAX= 2.370 MIN= -1.000
b
VELØCITY SPACE IN MAGNETØSPHERE AT T= 50.000
H
MAX= 1.168 MIN= -1.000
c

Figure 2



S3-3 SATELLITE DAY 211, 1976
FREQUENCY (kHz)
100.00
8.00
0.50
0.03
ELECTRONS, 235 keV
33.00
20.00
10.00
4.00
2.00
1.00
0.4
0.2
ELECTRON ENERGY (keV)
0.1
0.40
1.00
2.00
3.90
PROTON ENERGY (keV)
PROTONS >80 keV
UT 40600.0 40800.0 41000.0 41200.0 41400.0 41600.0 41800.0
INV LAT 68.2 70.5 72.6 74.6 76.4 78.0 79.3
MLT 19.6 19.3 19.1 18.7 18.3 17.8 17.2
ALT 7048.0 7274.0 7472.0 7641.0 7782.0 7893.0 7976.0
PITCH ANGLE
180
90
0

Figure 3

ELECTRONS
DAY 211 YEAR 1976
41263 to 41285 U.T.

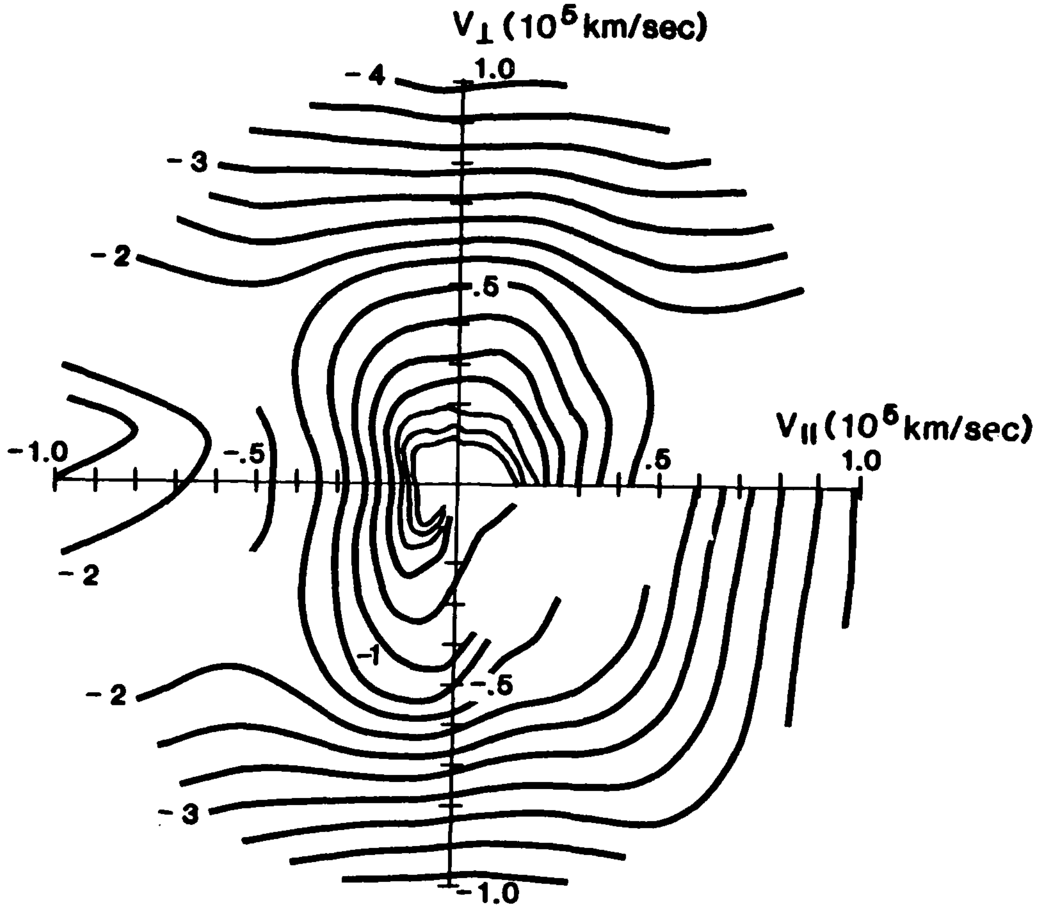


Figure 4